# Shallow Water Fluctuations and Communications

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## LONG TERM GOALS

The central effort of this research will be the development of robust algorithms for reliable, high data rate, acoustic communications in a dynamic ocean environment and demonstration of their use with data collected in a shallow water environment.

## OBJECTIVE

We will study shallow water fluctuation physics and the enhancement of performance of broad area acoustic communications in shallow water by building on developments in adaptive channel equalizers in conjunction with the time reversal approach.

## APPROACH

We have shown in recent work that the time reversal approach exploiting the *a priori* knowledge of the channel is applicable to underwater communications due to its spatial and temporal focusing capability. Temporal focusing (compression) mitigates the intersymbol interference (ISI) resulting from multipath propagation, while spatial focusing achieves a high SNR at the intended receiver with a low probability of interception elsewhere. The spatial focusing property enables a straightforward extension to multi-user/multi-access communications.

However, there are two major limitations in the time reversal (TR) approach. First, there always is some residual ISI which results in saturation of the performance. Second, time reversal assumes that the channel is time-invariant while the channel continues to evolve over time in a fluctuating ocean environment, resulting in a mismatch between the measured channel responses and the actual channel responses. To overcome these limitations, the time reversal approach will be combined with adaptive channel equalization which simultaneously eliminates the residual ISI and compensates for the channel fluctuations.

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## WORK COMPLETED

Indeed, it is confirmed using experimental data that the performance of time reversal alone can be improved significantly in conjunction with adaptive channel equalization [1,2]. In addition, it turns out that the combination provides nearly optimal performance in theory [2,3].

Using the spatial focusing property, we also have demonstrated multi-user communications where independent data streams were sent simultaneously from a time reversal array (equivalent to a base station in wireless channel) to different users (depths) at an 8.6 km range in 105-m deep shallow water, achieving an aggregate spectral efficiency of up to 3 bits/s/Hz [4].

## RESULTS

*Theory*

The system under consideration is illustrated in Fig. 1 where active time reversal (TR) is followed by a linear equalizer. When a known signal $g_0(t) = s(t)$ is transmitted from a probe source in a waveguide, the (noiseless) received signal on the $i^{\text{th}}$ element of the TR array is $r_i(t) = s(t) * c_i(t)$ where $c_i(t)$ is the channel impulse response of the waveguide and $*$ denotes convolution. The $N$-element TR array then retransmits the time reversed version of the received signal $r_i(-t)$. The signal received back at the original PS position, $s_{ps}(t)$ can be written as:

$$s_{ps}(t) = s(-t) * \left[ \sum_{i=1}^{N} c_i(t) * c_i(-t) \right] = s(-t) * q(t) \qquad (1)$$

where the term in the bracket has been called the $q$-function and is summed over the autocorrelation of each channel impulse response. The performance of the TR focus depends on the complexity of the channel $c_i(t)$ (i.e., the number of multipaths), the number of TR elements $N,$ and their spatial distribution (spatial diversity).

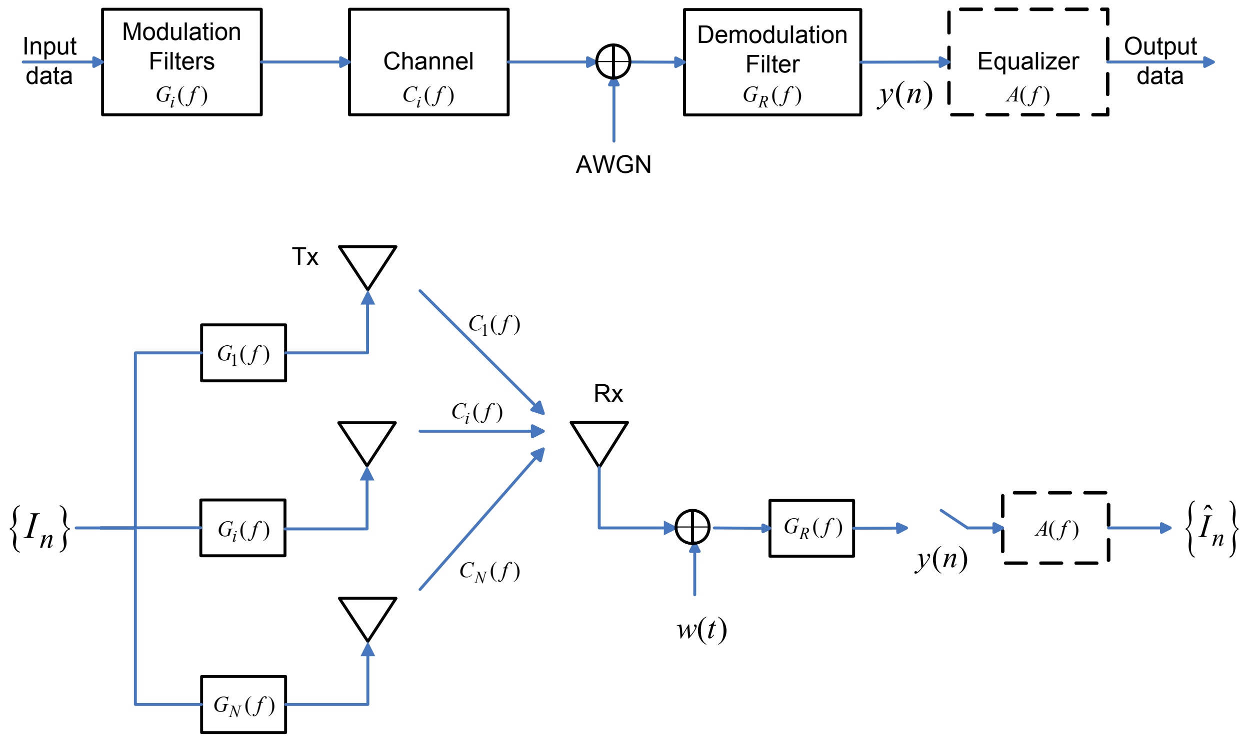


***Figure 1. System model for active (downlink) time reversal communications followed by a linear equalizer (dashed box).***

Figure 2 illustrates the performance improvement of TR with equalization over the case of TR alone when $N = 4$. We use a channel model with three multipaths (10-ms delay over a 3-km range) in 75-m deep water. The element spacing of the vertical array is chosen $d = 6\lambda$ to provide enough spatial diversity [3]. As expected, the performance of TR with residual ISI (square) saturates with an increasing $E/N_0$ whereas the performance of TR with equalization (circle) continues to improve. Although it is not shown here, the performance of TR with equalization is very close to that of optimal processing. The optimal processing is to simultaneously eliminate the ISI and maximize the SNR, while maintaining maximal data rate for a given bandwidth and satisfying a constraint on the transmitted energy. This suggests that we can relax the condition of zero ISI using TR at the front end while the overall system with equalization offers nearly optimal performance by removing the residual ISI. Thus, we can take full advantage of the spatial focusing property, allowing an extension of TR to MIMO multi-user/multi-access communications. For practical implementations, the benefit of this combination is that the number of taps required for an equalizer is much smaller than the case with just an equalizer alone, resulting in lower complexity at the equalizer.

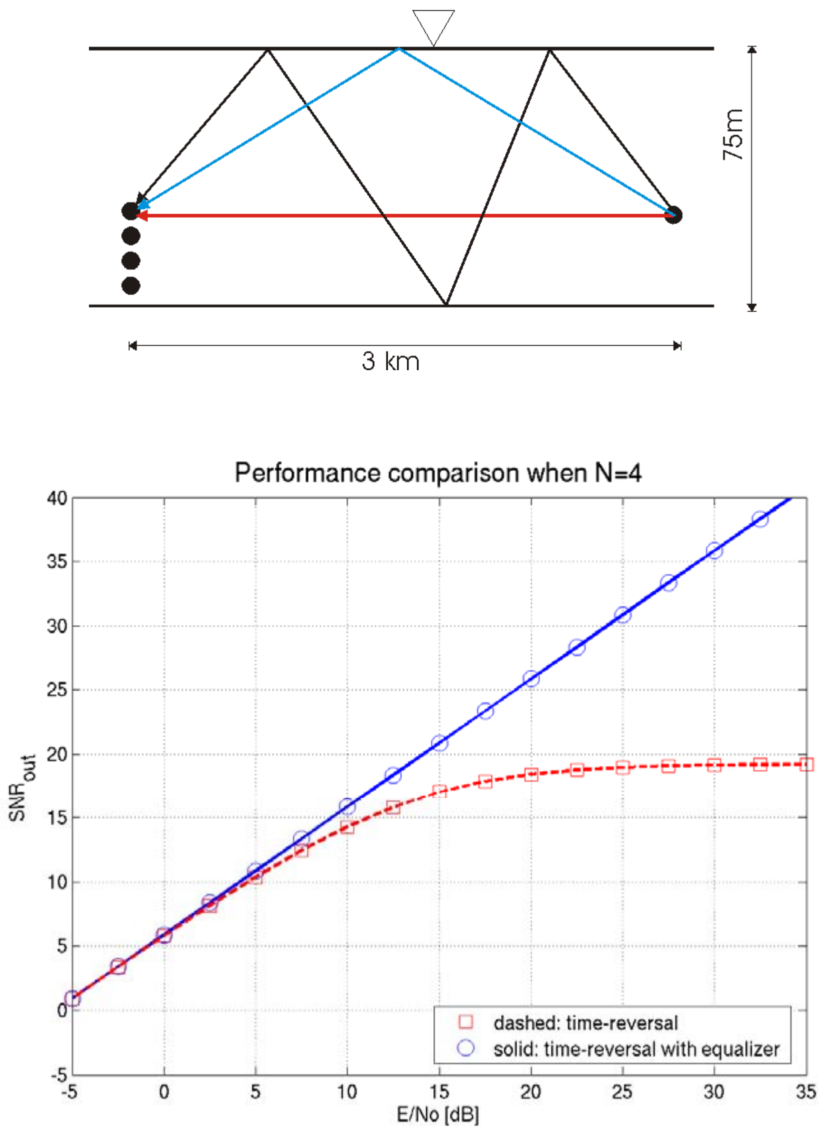


***Figure 2. Theoretical performance bounds for a waveguide model with three multipaths: TR with residual ISI (red square) and TR with equalization (blue circle).***

*Experimental Results*

A time reversal communications experiment was conducted jointly with the NATO Undersea Research Centre in July 2004 south of Elba Island, off the west coast of Italy. A probe source and a time reversal array were separated by 2-km range in 50-m deep water. We used a 150-ms, 2.5-4.5 kHz chirp with a Hanning window for a probe signal $s(t)$, resulting in an effective 100-ms, 3-4 kHz bandwidth chirp. The symbol interval was $R = 1/T = 500$ symbols/s, half the signal bandwidth of 1 kHz. We employed a nonlinear decision-feedback equalizer (DFE) as shown in Fig. 3 and used a fractionally spaced equalizer (FSE) with $T/4$ which provided the best performance [2].

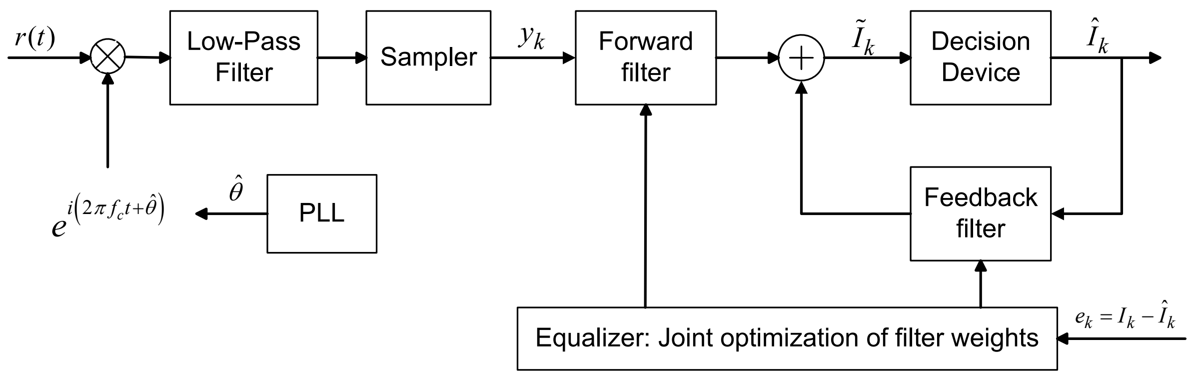


***Figure 3. Block diagram showing time reversal communications followed by a DFE equalizer. Note that a phase tracking using a DFPLL (decision-feedback phase-locked loop) has been carried out prior to the equalizer.***

Figure 4 displays the result of 32-QAM (quadrature amplitude modulation). The input SNR was 44 dB, but the performance of TR alone (left) indicates saturation due to the residual ISI for this high-order constellation. The bit error rate (BER) amounts to 5.4%. The scattered plot shown on the right side highlights the performance improvement of TR combined with an adaptive DFE, showing a completely open eye pattern.

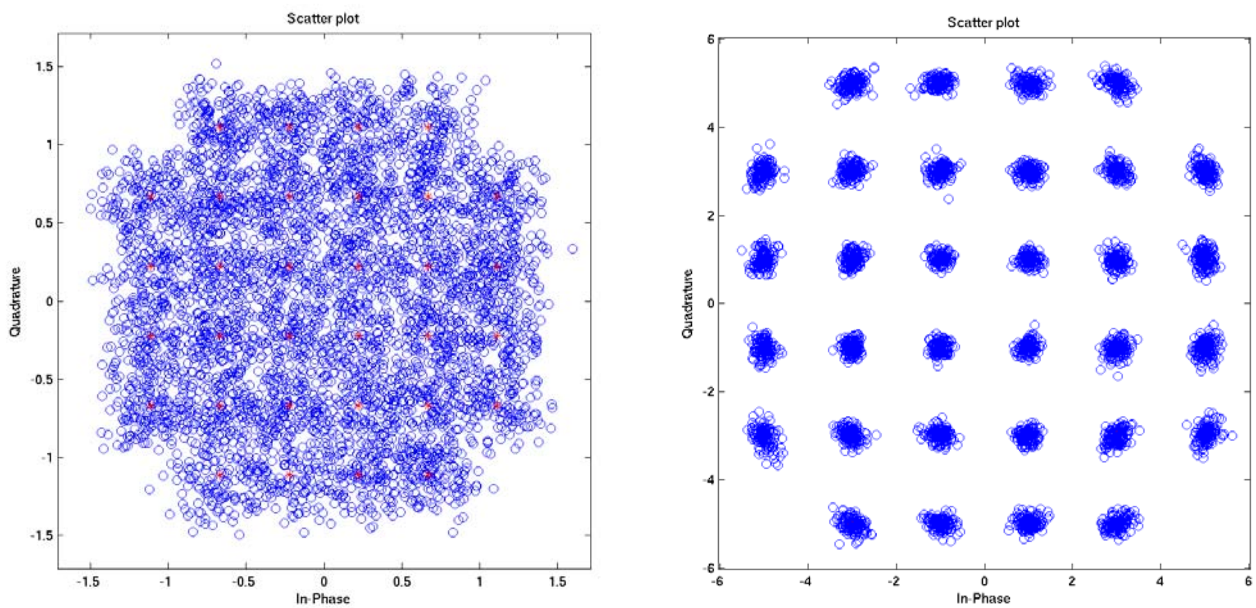


***Figure 4. Performance of 32-QAM modulation: (a) time reversal alone (left) and (b) time reversal in conjunction with an adaptive DFE (right). The input SNR was 44 dB. The output SNR was 14 and 26 dB, respectively.***

Finally, Figure 5 shows the results of QPSK signals transmitted to three receivers (users) simultaneously, resulting in a total data rate of 3 kbits/s. The input SNRs are 25.5, 27.7, and 29.7 dB, respectively and the worst performance of the first user (BER=7/9800) is due to the lower SNR while the other two users are error-free [4].

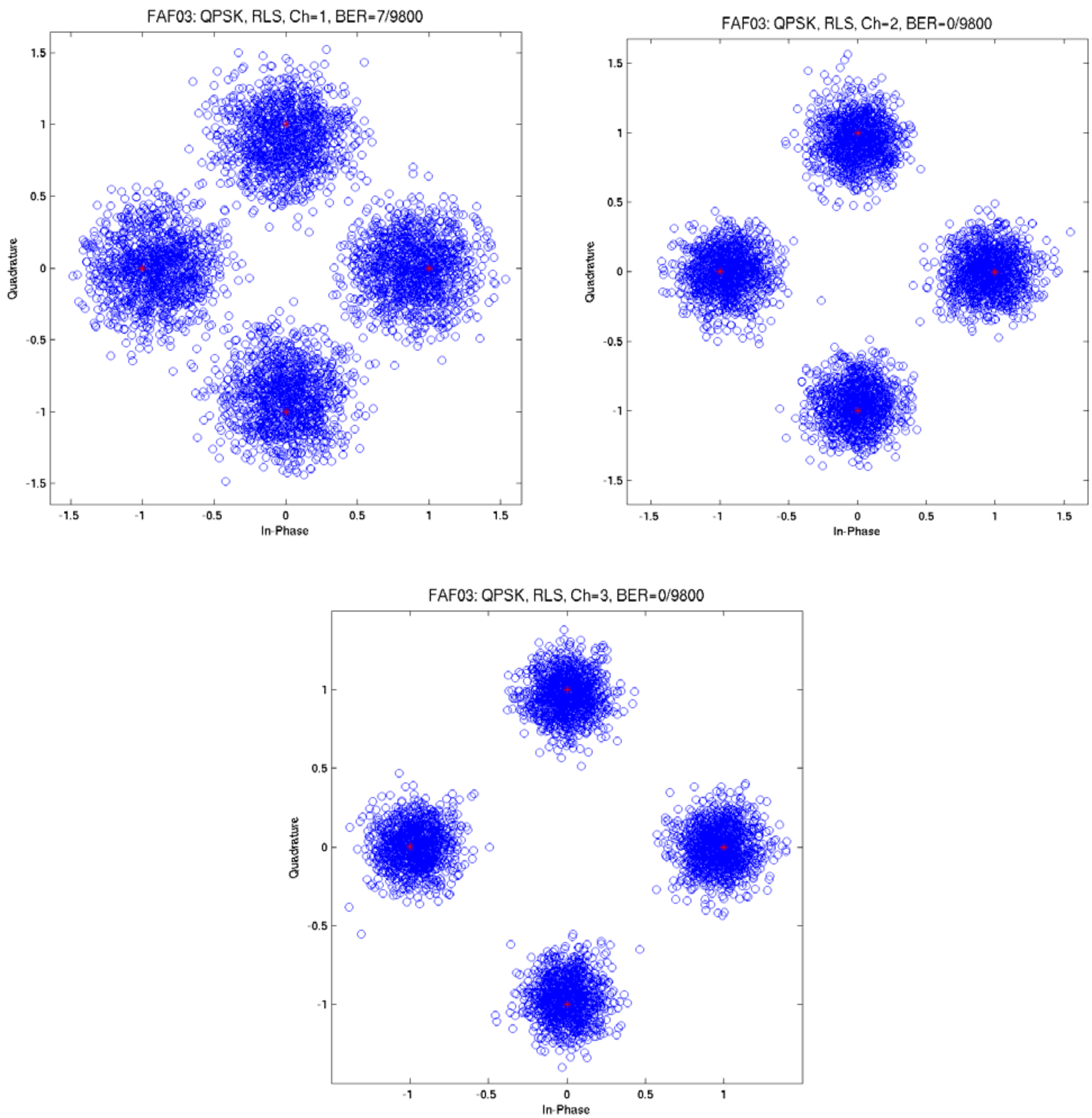


***Figure 5. Simultaneous three user communications using QPSK modulation over 8.6 km range in a 105-m deep shallow water.***

## IMPACT/APPLICATIONS

Time reversal is a concept recently introduced to the underwater acoustic community. The two-way (active) TR process provides a self-equalization that significantly reduces the ISI inherent in multipath ocean environments. Consequently, the TR receiver is simple to implement as compared to a typical multi-channel equalization approach. In addition, we can overcome the limitations of the time reversal approach (e.g., residual ISI and mismatch) by cascading time reversal with an adaptive channel equalizer, which provides nearly optimal performance. Note that channel equalization is applied to a single time-series at the focal spot (intended receiver) in active time reversal. In passive time reversal where the communications link is in the opposite direction, the multi-channel data is combined numerically to form a single time-series prior to channel equalization [5,6]. Furthermore, the self-averaging process of the time reversal approach using spatial diversity provides more robustness in the processing such that longer duration data packets can be transmitted.

## PUBLICATIONS


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